

Article

Probabilistic Characteristics Study of Tensile Properties of Bamboo Inter-Node Material Based on Random Field Theory

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Abstract

Driven by the low-carbon transformation in the construction industry, Moso bamboo has emerged as a promising green material. However, a critical gap exists in current structural design theories: they predominantly rely on homogeneous assumptions, failing to capture the inherent spatial variability and coupled strength–stiffness degradation of bamboo. Experimental results reveal a distinct longitudinal gradient, where the top section (5–8 m) exhibits approximately 15% higher average tensile strength and 12% higher average elastic modulus compared to the bottom section (1–3 m). This oversight severely compromises the accuracy of structural reliability evaluations. To address this, this study pioneers a high-precision digital representation method by developing a novel three-dimensional (3D) anisotropic bivariate coupled random field model. Experimental and stochastic finite element simulations demonstrate that the model accurately replicates spatial variations, maintaining relative errors for primary statistical indicators strictly below 1% while robustly capturing the bivariate coupling characteristics. Crucially, by integrating non-parametric probability box (P-box) theory, the macroscopic tensile resistance of full-scale bamboo members is rigorously bounded within a definitive statistical interval. Furthermore, the extracted Interval Skewness Ratio generally remains greater than 1.0 (averaging 1.38), providing robust quantitative proof of an asymmetric structural degradation governed by the brittle weakest-link failure mechanism. By effectively eliminating non-physical sample generation associated with traditional univariate models, this research makes a significant contribution to the field, providing a rigorous digital twin framework and theoretical foundation for the advanced non-probabilistic safety design of modern bamboo structures.



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Keywords: Moso bamboo; tensile performance; spatial variability; three-dimensional random field; bivariate coupling

1. Introduction

Driven by the macro-strategies of low-carbon transition in the construction industry and the “dual-carbon” goals, Moso bamboo, as a natural biomass material with strong carbon sequestration capacity, rapid growth, and renewability, demonstrates broad application prospects in modern civil engineering. However, the current state of the issue regarding the structural application of solid bamboo is not yet sufficiently addressed. Recent reviews

emphasize that natural variability, geometric irregularities, and the need for sorting and classification are key limitations hindering the adoption of full-culm bamboo as a mainstream structural material [1]. Under the combined influence of natural environmental factors such as climate, soil, illumination, and bamboo age, the internal microstructure and macroscopic mechanical properties of Moso bamboo exhibit significant spatial variability along its longitudinal, radial, and circumferential directions. Current bamboo structural design theories are generally based on homogeneous and deterministic assumptions, neglecting this inherent continuous gradient and local fluctuation. This oversight easily leads to an overestimation of member resistance or material waste caused by the blind adoption of excessively large safety factors.

Numerous experimental studies have shown that the macroscopic mechanical properties of Moso bamboo present a significant gradient variation pattern on a spatial scale. In the axial dimension, the various mechanical strengths of Moso bamboo generally increase progressively from bottom to top, and the influence of height position on tensile strength is particularly pronounced [2,3]. In the radial dimension, this non-homogeneity is even more drastic: from the outer layer (near the bamboo cortex) to the inner layer (near the bamboo pith), the parallel-to-grain tensile elastic modulus and tensile strength show a significant attenuation trend. The strength of the outermost layer can even reach two to three times that of the innermost layer, accompanied by a transition in failure mode from fiber tearing to flat transverse fracture [4–6].

The physical root of this macroscopic variation is essentially governed by the spatial distribution and microstructural characteristics of mesoscopic vascular bundles. Recent studies have specifically examined the radial variation in vascular bundles in Moso bamboo, revealing how their arrangement, cross-sectional area, and mechanical properties continuously evolve along the radius of the bamboo wall [7]. Studies have confirmed that the volume fraction, distribution density, and multi-wall island-chain structure of vascular bundles serve as the core foundation for providing tensile stiffness and ultimate stress [8–13]. A strong positive correlation and linearly increasing trend exist between the parallel-to-grain tensile mechanical properties of Moso bamboo and the vascular bundle volume fraction [14–18]. Therefore, when conducting large-sample testing and reliability analysis, it is imperative to abandon the single-value assumption and accurately quantify this high dispersion induced by the gradient distribution of vascular bundles [19].

To authentically characterize the spatial variability and short/long-range dependence features within non-homogeneous materials, Vanmarcke et al. introduced random field theory into the field of engineering mechanics, accurately describing the spatial attenuation laws of material properties through autocorrelation functions [20–22]. Currently, various mature random field discretization methods (e.g., Local Average Subdivision, Karhunen–Loève expansion) have been widely applied in the full-life performance evaluation and extreme failure risk quantification of engineering materials such as soils, concrete, and tunnels [23–36]. In recent years, some scholars have begun to treat Moso bamboo as a natural functionally graded material, innovatively introducing random field methods to quantify its strain response differences under tension and compression [37].

However, a critical review of the existing literature reveals a precise research gap: while current studies have widely identified the macroscopic non-homogeneity and microscopic physical mechanisms of Moso bamboo [1–19], and mature random field models have been adopted for other structural materials [20–36], the specific application of these probabilistic models to bamboo remains insufficiently developed. Existing reliability assessments for bamboo largely rely on independent univariate models. Significant theoretical gaps remain in the three-dimensional high-precision modeling and multivariate physical coupling characterization of bamboo's mechanical properties. Traditional univariate assumptions

fail to replicate the genuine physical synergistic mechanism between tensile strength and elastic modulus, which are both intrinsically governed by the same vascular bundle distribution network.

In view of this, conducting this research holds urgent engineering necessity and profound theoretical significance. Taking Moso bamboo as the research object, and based on 255 sets of large-sample parallel-to-grain tensile tests alongside the extraction of vascular bundle volume fractions via digital image processing technology, this paper innovatively proposes and constructs a “three-dimensional anisotropic bivariate coupled random field model”. This study aims to break the limitations of traditional homogeneous assumptions and independent univariate models, strictly restore the natural physical synergistic mechanism between tensile strength and elastic modulus from the mathematical foundation, and accurately reconstruct the spatial distribution of continuous weak zones within Moso bamboo members. Consequently, this provides a high-fidelity digital twin characterization method for Moso bamboo materials and offers solid theoretical support for the subsequent high-precision and refined reliability design of bamboo structures.

The flowchart is presented in Figure 1 below.

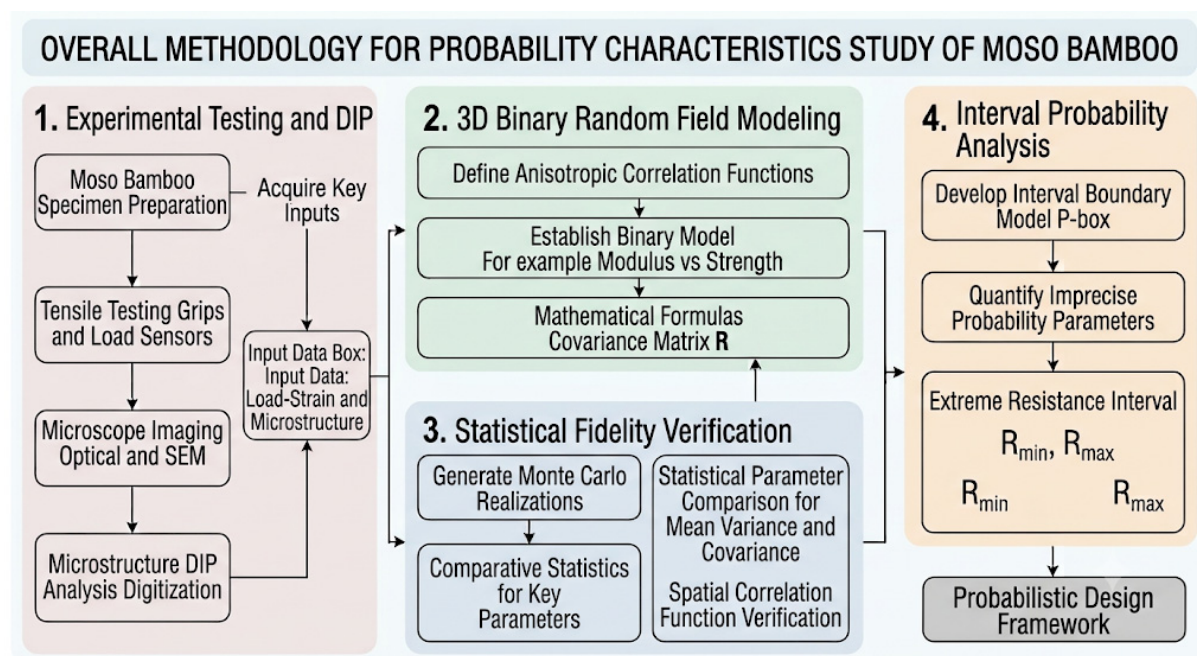


Figure 1. Technical flowchart of the research.

2. Experimental Study on the Tensile Properties of Moso Bamboo Specimens

2.1. Materials and Specimen Preparation

The raw material utilized was healthy Moso bamboo from a single batch, rigorously screened for consistency (culm age: 4–5 years, growth height: 6–8 m, outer diameter ≥ 100 mm, and free of apparent defects). Starting from the base, three longitudinal sections were extracted from each culm at 1.5 m intervals to capture the natural gradient variations. These sections were processed into bamboo strips and further divided into individual tensile specimens.

After discarding specimens severely damaged during the splitting process, a total of 280 valid specimens were obtained. Ten replicates were prepared for each group. For exact traceability, each specimen was assigned a unique ID (detailed in Table 1) consisting of the culm number, a section letter ('S' for top, 'Z' for middle, and 'X' for bottom), and a specific piece number.

The spatial coordinates—longitudinal height, radial depth, and circumferential angle—were precisely recorded for each specimen. The geometric configuration of the tensile specimens is illustrated in Figure 2. The total length was unified at 150 mm, with a central gauge section of 70 mm. (The blue lines indicate the effective part of the bamboo strip during the tensile test.) The gauge cross-section was machined to $8 \text{ mm} \times t$, where t represents the individually measured maximum thickness of the strip retaining the bamboo cortex. Throughout the machining process, the inclusion of bamboo nodes within the gauge section was strictly avoided. Figure 3 shows the schematic diagram of the whole bamboo and some of the cut original bamboo strips, while the specific grouping details and the quantity of specimens in each group are listed in Table 1.

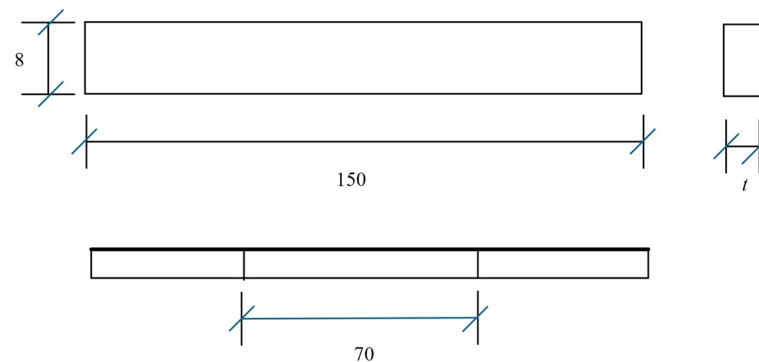


Figure 2. Dimensions of Moso bamboo tensile specimens.

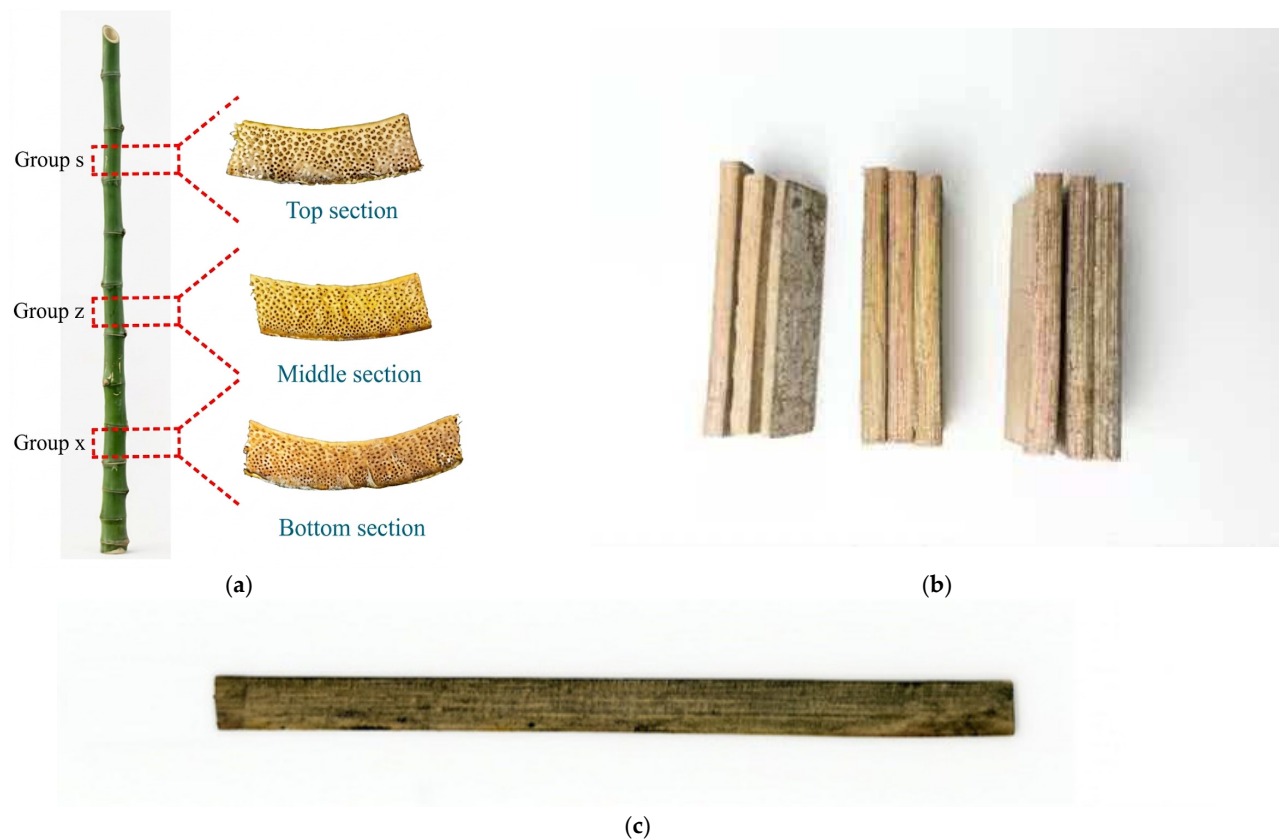


Figure 3. (a) Schematic diagram of a whole bamboo culm. (b) Partial bamboo strips after cutting. (c) Processed Moso bamboo Tensile Specimens.

The fabrication of the Moso bamboo tensile specimens was controlled and executed using a digitally controlled machine tool at the machining center, resulting in a final

total of 280 specimens. Following the machining process, the width and thickness of the cross-section within the gauge area were measured with an accuracy of one decimal place. Subsequently, strain gauges were attached to the tensile gauge section of the specimens.

Table 1. Grouping of Moso bamboo tensile specimens and the number of specimens in each group.

Location of Bamboo Section	Group	Number of Specimens
Top section (5–8 m)	Top group (Group S)	96
Middle section (3–5 m)	Middle group (Group Z)	93
Bottom section (1–3 m)	Bottom group (Group X)	91

2.2. Microscopic Morphology Acquisition and Digitization Preparation of Moso Bamboo

As a typical fiber-reinforced biomass composite material, the macroscopic mechanical strength of Moso bamboo fundamentally depends on the distribution density and spatial arrangement logic of vascular bundles at the micro-scale. To transform these qualitative biological structural characteristics into quantitative numerical simulation parameters, this study introduces digital image processing technology to characterize the microscopic morphology of the 280 sets of measured specimens. The microscopic samples were observed and recorded using a microscope.

A cross-sectional slice with a thickness of approximately 1.5 mm was cut from the area adjacent to the fracture of each specimen. The slices were fixed using a custom-made cold resin embedding mold to mitigate potential surface burrs. Fine grinding was performed using an automatic metallographic polishing machine with sequentially applied 800-, 1200-, 2000-, and 3000-grit silicon carbide sandpaper to ensure a flat, uniform surface for microscopic observation.

Image acquisition was performed using a 3D microscope (VHX series, Keyence Corporation, Osaka, Japan). To ensure the accuracy of the subsequent random field modeling, the image resolution was uniformly set to 2400a, guaranteeing that the physical size of a single pixel was much smaller than the diameter of a single fiber. During the acquisition process, an annular cold light source was used for compensation, and the exposure time and contrast gain were strictly controlled. This ensured that the dark vascular bundle regions and the light parenchyma cell matrix exhibited distinct bimodal characteristics on the histogram. Figure 4 shows the magnified image of the original bamboo obtained using the 3D microscope.



Figure 4. Enlarged image of Moso bamboo under 3D microscope.

2.3. Image Preprocessing and Feature Enhancement Algorithms

The originally acquired digital images contain substantial color noise and brightness shifts caused by uneven illumination, which must be optimized through systematic preprocessing operators. Since the lignin and cellulose in Moso bamboo exhibit different reflectances under various hues, a weighted average method is employed to convert the RGB color images into grayscale images. The calculation logic is as shown in the equation:

$$Gray = 0.299R + 0.587G + 0.114B \quad (1)$$

where R , G , and B represent the red, green, and blue channels, respectively. By performing a weighted average of the values from these three channels according to specific weights, the corresponding grayscale value can be calculated. This algorithm maximizes the preservation of detailed features at the edges of the vascular bundles, thereby improving the signal-to-noise ratio of the images.

Homomorphic Filtering: To address the uneven reflectance of the Moso bamboo cross-section caused by its physiological structure, a homomorphic filtering algorithm was introduced. By compressing the brightness range and enhancing the contrast in the frequency domain, low-frequency interference in the image background is eliminated. This ensures a consistent brightness baseline across the entire image, avoiding under-segmentation or over-segmentation phenomena in the subsequent global thresholding segmentation.

Median Filtering: A 5×5 square structuring element was adopted to perform median filtering on the grayscale images. Compared with linear filtering, median filtering can effectively remove isolated noise points generated by the vessel pores of the bamboo without blurring the physical boundaries between the vascular bundles and the matrix. This ensures the invariance of geometric properties such as perimeter and area. Figure 5 shows the filtered and enhanced image of the original bamboo.

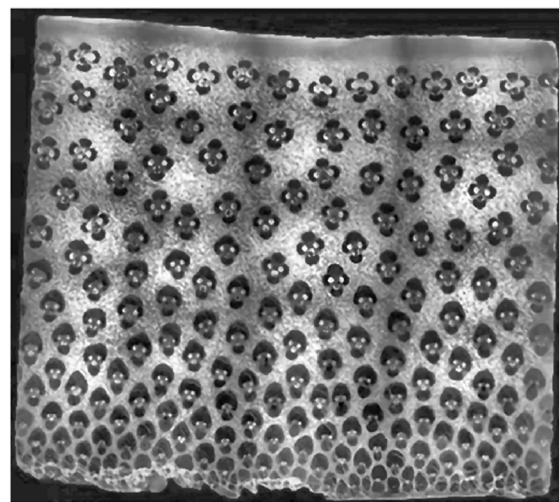


Figure 5. Filter-enhanced image of Moso bamboo.

2.4. Automated Segmentation and Binarization Logic Construction

In the finally generated binarized image, a pixel value of 1 represents the high-strength vascular bundle, while 0 represents the loose parenchyma cell matrix.

The calculation logic is formulated as follows: The vascular bundle volume fraction is defined as the ratio of target pixels to the total pixels within the effective observation area:

$$V_f = \frac{1}{N_{total}} \sum_{i=1}^M \sum_{j=1}^N I(i, j) \times 100\% \quad (2)$$

where V_f is the vascular bundle volume fraction; and $I(i, j)$ is the function value of the binarized image at coordinates (i, j) . M and N represent the number of rows and columns of pixels in the image; and N_{total} is the total number of pixels after excluding the external invalid regions.

Otsu's method was employed to automatically determine the optimal segmentation threshold T by maximizing the variance between vascular bundles and parenchyma. A morphological closing operation was subsequently applied to fill internal micro-voids within vascular bundles while preserving overall contours. Based on stereological principles, the vascular bundle volume fraction was calculated as the ratio of target pixels to total pixels within the effective observation area. Figure 6 shows the binarized segmentation image of the original bamboo cross-section.

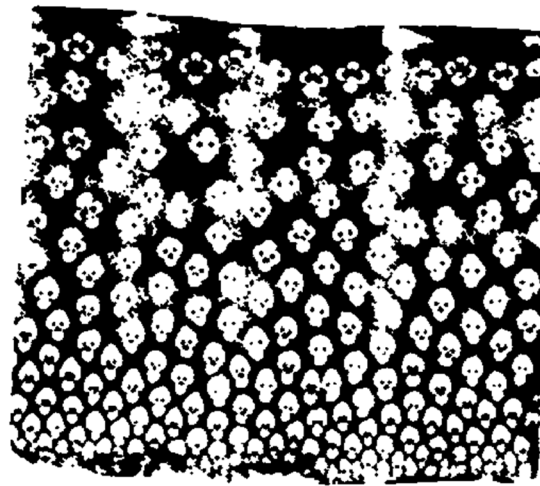


Figure 6. Binarized segmentation image of Moso bamboo.

2.5. Moso Bamboo Tensile Testing

During the parallel-to-grain tensile testing of the Moso bamboo specimens, the experimental procedures were conducted with reference to the JG/T 199-2007 standard [38] (testing methods for physical and mechanical properties of bamboo used in building). The parallel-to-grain tensile elastic modulus was determined based on the stress–strain relationship within the proportional limit. Specifically, the modulus was calculated from the slope of the linear elastic region, utilizing the data range corresponding to 10% to 40% of the maximum ultimate load. Similarly, the parallel-to-grain ultimate tensile strength was calculated based on the ratio of the maximum ultimate load to the cross-sectional area.

The tests were conducted using a universal testing machine (SHIMADZU AGX-5 kN, Kyoto, Japan) equipped with a static data acquisition system. Although the specific equilibrium moisture content and density of each individual sample were not quantitatively measured prior to testing, strict measures were taken to ensure environmental consistency. All specimens, originating from the same harvested batch, were stored together in the controlled laboratory environment (room temperature of 30 °C and a relative humidity of 75%) for 3 weeks prior to the experimental campaign. This uniform conditioning period ensured that all samples reached a similar equilibrium moisture state, thereby confirming that the observed mechanical dispersion is primarily attributable to the material's intrinsic microstructural variability. Prior to testing, it was carefully verified that the specimen was aligned parallel to the loading centerline, and that the tangential direction of the side near the bamboo cortex was perpendicular to the gauge section (the central gauge length being 70 mm).

During the test, each end of the specimen was gripped over a length of 40 mm. To prevent local crushing failure and grip slippage, the ends were secured using mechanical wedge grips equipped with anti-slip emery cloth pads. Uniaxial tension was continuously applied by the testing machine at a loading rate of 1 mm/min until an apparent fracture occurred. Figure 7 illustrates a Moso bamboo tensile specimen undergoing fracture during the testing process.

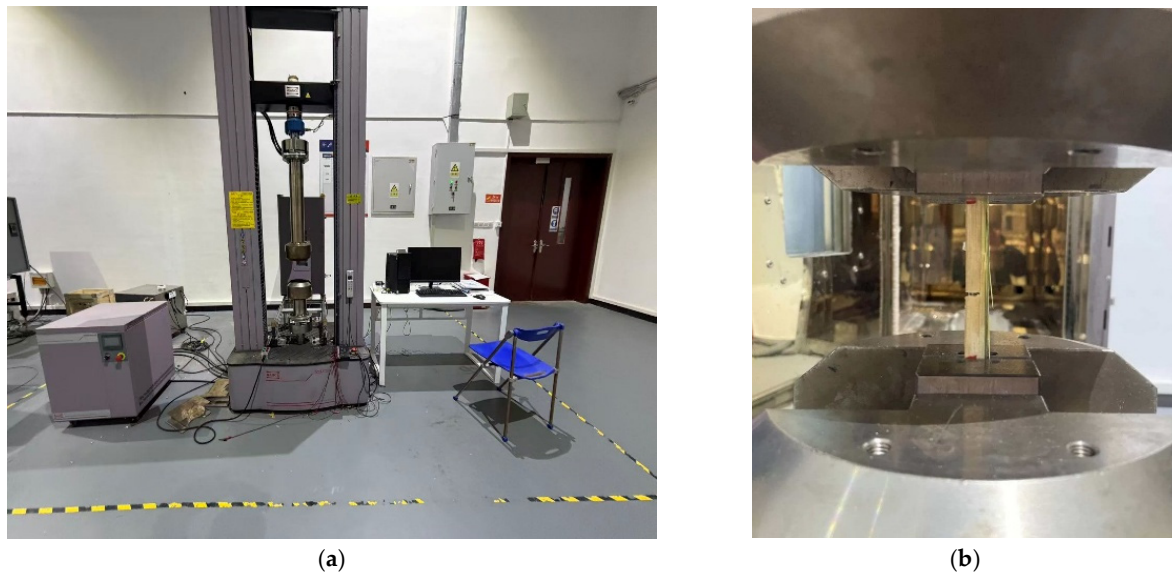


Figure 7. Tensile test of Moso bamboo: (a) Universal testing machine; (b) Moso bamboo tensile specimen during testing.

Using a universal testing machine, the data spanning the entire tensile process were comprehensively recorded and saved in Excel files. Subsequently, Origin 2024 software was utilized to plot the stress–strain curves. Figure 8 illustrates the tensile stress–strain curves of the Moso bamboo specimens from the three longitudinal sections.

Analysis of the figure reveals that during the initial loading phase, the stress–strain curve of the parallel-to-grain axial tensile specimens basically exhibits a linear relationship, with the curve rising linearly. During this stage, the tensile stress is primarily borne by the dense and tough longitudinal vascular bundles on the outer side (bamboo cortex), while the parenchyma tissue on the inner side (bamboo pith) undergoes synergistic deformation. The stress is distributed relatively evenly throughout the material, causing the specimen to experience recoverable elastic deformation. As the stress approaches the lower limit of the material's local strength, slight, macroscopically invisible micro-damage begins to initiate at the weakest micro-defects.

When the stress exceeds the proportional limit, the curve enters a non-linear stage where micro-damage begins to steadily accumulate. Although in situ SEM analysis was not conducted in this study, the systematic visual inspection of the 255 failed specimens (as representatively shown in Figure 8b) reveals a highly consistent macroscopic fracture morphology. The failure typically initiated at the weaker bamboo pith side, where the parenchyma matrix is abundant. As the load increased, longitudinal cracks propagated rapidly along the weak parenchyma matrix or the fiber-matrix interfaces, leading to distinct longitudinal splitting.

The final catastrophic failure occurred when the dense longitudinal vascular bundles on the bamboo cortex side fractured transversely, leaving a rough, brush-like cross-section. These systematic macroscopic fracture features, combined with the acoustic emissions recorded during the non-linear loading stage, perfectly align with the classic microscopic

failure mechanisms of bamboo—specifically, interfacial debonding followed by fiber bridging and breakage—which have been extensively documented and verified by authoritative SEM studies [4,19]. Therefore, this macroscopic fracture description robustly supports the observed stress–strain behavior.

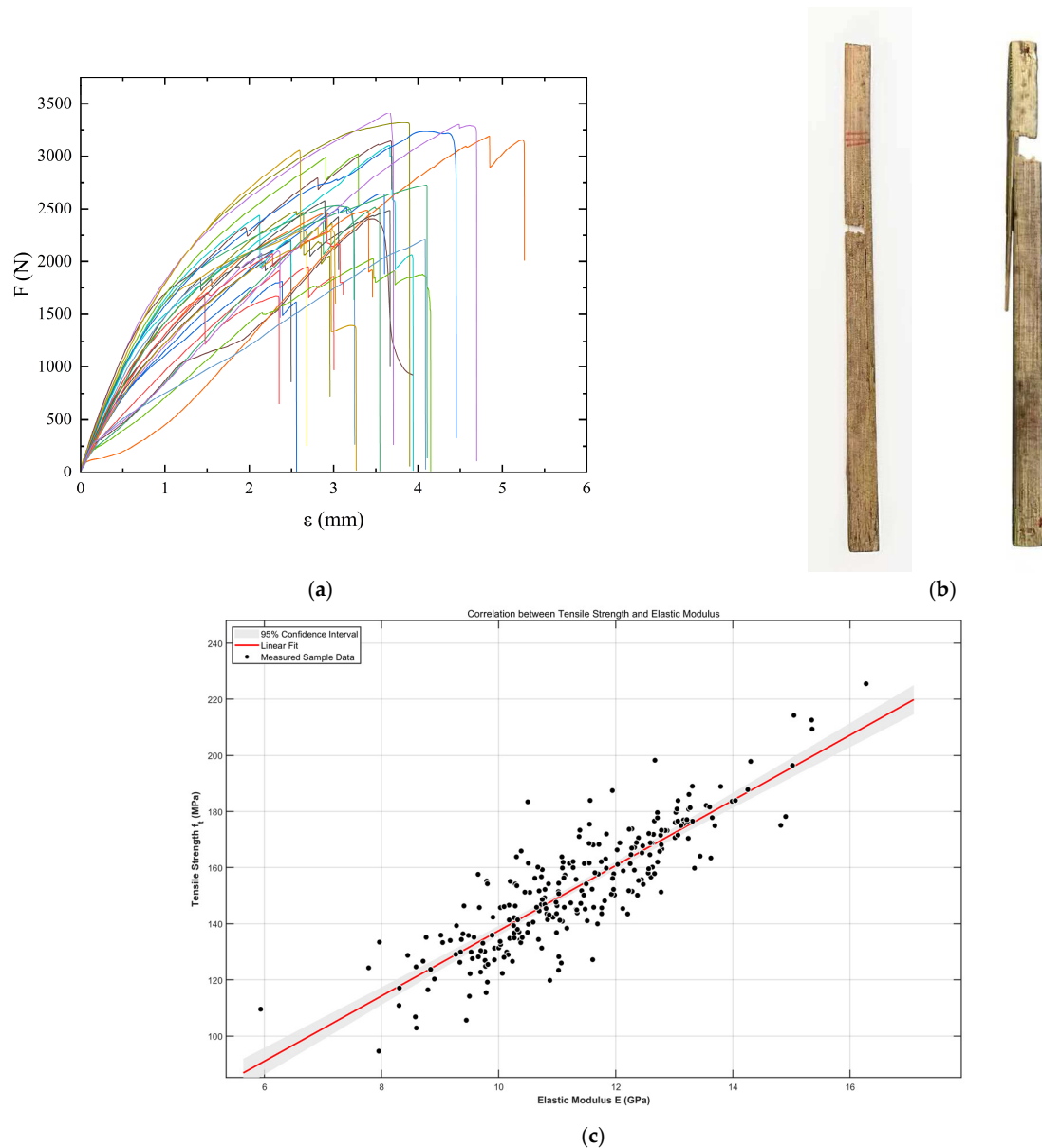


Figure 8. (a) Tensile force–displacement curves of some specimens. (b) Transverse tensile failure and end failure specimen. (c) Correlation between Tensile Strength and Elastic Modulus.

In this test, some specimens exhibited end failure as the failure mode, as shown in the right image of Figure 8b. This is a non-ideal failure pattern that occurs in the contact area between the specimen and the grips. Typical characteristics include the failure location being adjacent to the grips, often showing local crushing, tearing, or mixed cracks. This is due to the high clamping pressure and significant stress concentration in this region. The main causes are that excessive clamping pressure leads to local crushing of bamboo fibers at the contact point; meanwhile, misalignment between the specimen and the grips introduces additional bending or shear stresses, further exacerbating the stress concentration effect, thereby causing premature failure outside the effective gauge length. Therefore, specimens exhibiting this type of failure are excluded from strength calculations.

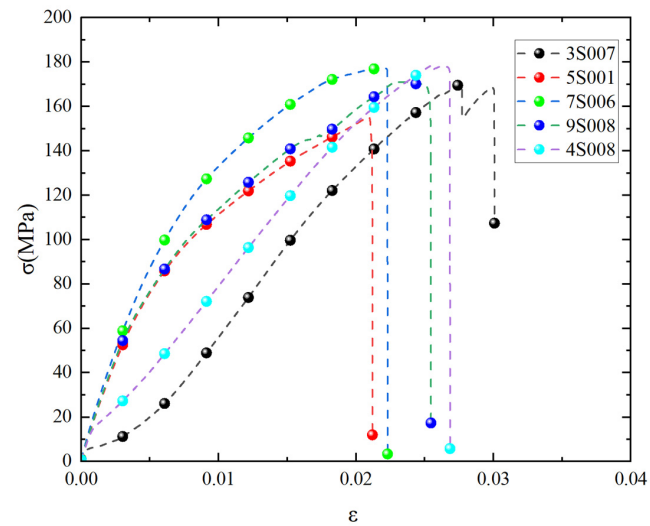
The test data from the Moso bamboo tensile experiments in Appendix A Table A1 were analyzed, and the results are summarized in Table 2. During the tensile testing process, several specimens experienced end failure. Consequently, a total of 255 sets of valid data were ultimately obtained from this study. As indicated by the analytical results, the maximum, minimum, and average tensile strengths of the Moso bamboo specimens were 224.60 MPa, 93.08 MPa, and 151.71 MPa, respectively. Similarly, the maximum, minimum, and average values of the elastic modulus were 16.62 GPa, 6.93 GPa, and 11.3 GPa, respectively.

Table 2. Tensile strength and elastic modulus of Moso bamboo specimens in each group.

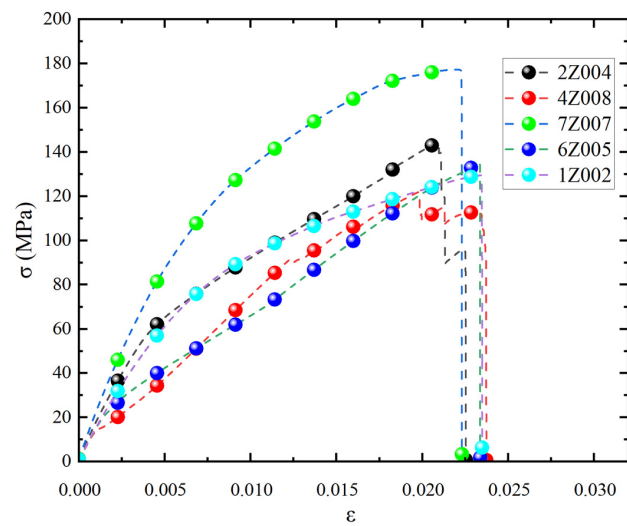
Group	Tensile Strength Statistics				Elastic Modulus Statistics			
	Max (MPa)	Min (MPa)	Mean (MPa)	COV	Max (GPa)	Min (GPa)	Mean (GPa)	COV
1S	208.29	140.35	168.08	12.7%	15.42	10.33	12.42	12.9%
1Z	183.59	129.37	164.05	10.9%	13.52	9.02	12.08	12.1%
1X	183.30	103.25	151.87	15.3%	13.59	7.61	11.25	15.4%
2S	185.32	105.47	151.64	17.0%	13.81	7.87	11.25	16.9%
2Z	178.90	109.33	144.64	14.0%	13.25	8.17	10.77	15.8%
2X	163.59	117.94	137.80	11.8%	12.13	8.75	10.16	12.3%
3S	175.18	113.47	147.44	16.2%	14.02	8.40	11.05	17.8%
3Z	172.19	137.03	156.68	9.2%	12.77	10.17	11.60	9.2%
3X	158.65	119.61	136.49	10.2%	11.76	8.86	10.12	10.2%
4S	185.83	128.10	159.14	14.9%	13.79	9.57	11.55	14.1%
4Z	166.59	130.99	142.14	8.7%	12.30	9.65	10.53	8.5%
4X	171.89	99.14	144.44	14.4%	12.68	9.02	11.17	9.6%
5S	183.24	130.00	151.86	9.5%	13.55	9.68	11.31	9.7%
5Z	186.37	127.03	149.90	13.6%	13.79	9.41	11.11	13.6%
5X	169.29	116.35	146.29	11.5%	12.51	8.61	10.83	11.5%
6S	204.58	122.08	161.34	15.3%	15.05	9.09	11.92	15.0%
6Z	169.39	116.26	147.36	11.3%	12.51	8.61	11.17	10.3%
6X	180.25	93.08	147.25	20.9%	13.37	6.93	10.89	21.2%
7S	211.08	106.90	163.81	22.8%	15.59	7.79	12.11	23.0%
7Z	176.52	131.05	152.66	9.2%	11.82	9.73	10.97	7.2%
7X	166.50	111.08	140.46	14.4%	12.28	8.27	10.41	14.0%
8S	213.64	136.93	170.33	13.3%	15.81	10.06	12.59	13.5%
8Z	165.99	124.99	142.34	10.5%	12.28	9.29	10.53	10.5%
8X	181.07	106.80	153.30	14.2%	13.38	10.57	11.67	14.2%
9S	224.60	127.10	167.44	18.2%	16.62	9.44	12.40	18.1%
9Z	183.35	122.37	153.21	15.5%	13.57	9.03	11.33	15.5%
9X	179.81	105.68	147.32	17.0%	13.32	7.83	10.91	17.0%
10S	199.84	129.13	156.31	14.6%	14.83	9.61	11.59	14.6%
10Z	184.78	125.56	151.04	14.5%	13.65	9.31	11.19	14.4%
10X	172.99	117.16	145.26	11.7%	12.82	8.69	10.75	11.6%

Origin data analysis software was utilized to analyze the parallel-to-grain tensile stress–strain curves of the Moso bamboo. Figure 9 shows the parallel-to-grain tensile stress–strain curves of some specimens at different ends. The following figures present the parallel-to-grain tensile stress–strain curves for selected specimens from different longitudinal sections. As observed from the figures, during the initial loading phase, the parallel-to-grain tensile stress–strain relationship of the Moso bamboo fundamentally exhibits a linear elastic growth trend, governed by Hooke’s law, as expressed in Equation (3).

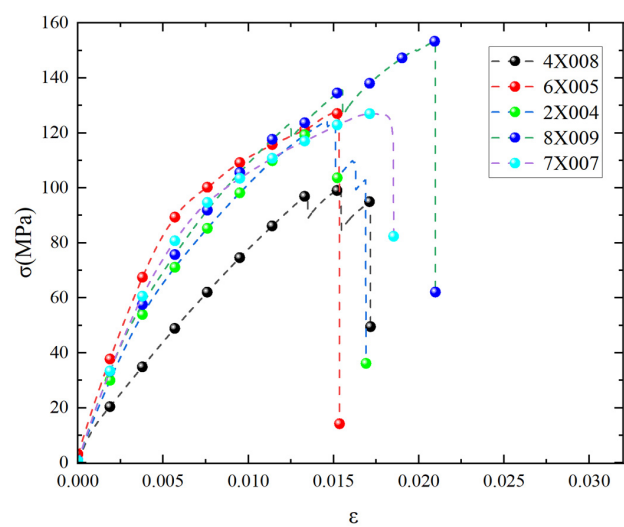
$$\sigma = E\varepsilon \quad (3)$$



(a)



(b)



(c)

Figure 9. Tensile stress–strain curves of selected specimens: (a) Tensile stress–strain curves of upper part specimens. (b) Tensile stress–strain curves of middle part specimens. (c) Tensile stress–strain curves of lower part specimens.

In the current tests, the maximum tensile strength of the Moso bamboo was 224.60 MPa, the minimum was 93.08 MPa, and the overall average was 151.71 MPa, with an average elastic modulus of 11.3 GPa. Although the average tensile strength of Moso bamboo is at a relatively high level, the data exhibits extremely strong dispersion. The coefficients of variation (CV) for the tensile strength of each group generally range from 8.5% to 23.0%, which is significantly higher than that of artificial homogeneous building materials such as steel and concrete.

From the group comparison in Table 2, it can be clearly observed that the mechanical properties of Moso bamboo present a distinct decreasing gradient pattern in the longitudinal direction, namely “Top section (Group S) > Middle section (Group Z) > Bottom section (Group X)”. The physical root of this phenomenon lies in the natural growth and evolution of Moso bamboo. The culm wall of the top section is thinner, with a denser arrangement of vascular bundles; conversely, the culm wall of the bottom section is thicker, and the proportion of low-strength parenchyma cells acting as fillers increases sharply, resulting in a decline in the fraction of effective load-bearing fibers per unit cross-sectional area.

The superposition of this strong spatial dispersion and gradient evolution introduces an inherent high uncertainty into the material’s mechanical behavior. This indicates that the structural design of Moso bamboo cannot directly adopt the traditional single safety factor method; instead, probability theory must be introduced for a rigorous evaluation.

3. Spatial Random Field Modeling of the Tensile Properties of Moso Bamboo

In the experimental research presented in the previous chapter, axial tensile tests were conducted on samples extracted from 10 Moso bamboo culms divided into three longitudinal sections (top section S, middle section Z, and bottom section X), yielding a total of 255 sets of valid data encompassing tensile strength, elastic modulus, and vascular bundle volume fraction. Simultaneously, the longitudinal height, radial depth, and circumferential angle of each specimen were recorded. The experimental data indicate that the mechanical properties of Moso bamboo not only exhibit significant gradient evolution characteristics along the growth height but also demonstrate random fluctuations at different angular positions within the same cross-section. However, the experimentally obtained data are discrete in their spatial distribution and cannot be directly applied to describe the continuous non-homogeneity of properties within Moso bamboo members. Therefore, utilizing the 255 sets of measured data as statistical inputs, this chapter calibrates the spatial anisotropic parameters of Moso bamboo and subsequently constructs a theoretical random field model. This model is designed to rigorously capture both the spatial correlation of strength and modulus, as well as the physical coupling mechanism between the two.

3.1. Basic Theory and Discretization Methods of Random Fields

Traditional independent random variable models fail to account for the spatial clustering and long-range coherence in Moso bamboo, underestimating weakest-link size effects. Random field theory is thus applied to characterize these spatial correlations.

Random field theory is fundamentally the extension of stochastic processes into multi-dimensional Euclidean space. From the rigorous mathematical perspective of measure theory, assume $(\Omega, \mathcal{F}, P)$ is a complete probability space, where Ω is the sample space, $\mathcal{F}$ is the σ algebra on the sample space Ω , and P is the probability measure defined on $\mathcal{F}$.

For the physical spatial domain $D \in \mathbb{R}^3$ occupied by the Moso bamboo culm wall, a random field $H(X, \omega)$ defined on D is a bivariate mapping. For any given spatial coordinate point $x \in D$, $H(x, \omega)$ is a random variable defined on the sample space Ω . Conversely, for

any given elementary event $\omega \in \Omega$, $H(x, \omega)$ constitutes a deterministic function over the space D , namely, a sample function of the random field.

In practical engineering applications, a continuous random field is primarily and uniquely determined by its first-order and second-order statistical moments:

Mean function: Characterizes the mathematical expectation of the random field at various spatial points, reflecting the macroscopic deterministic trend of Moso bamboo properties:

$$\mu(x) = E[H(x, \omega)] = \int_{\Omega} H(x, \omega) dP(\omega) \quad (4)$$

Variance function: Describes the degree of dispersion of the performance parameters around the expected value:

$$\sigma^2(x) = E\left[\{H(x, \omega) - \mu(x)\}^2\right] \quad (5)$$

Autocovariance function: This is the core operator that distinguishes a random field from a random variable, quantifying the coherent relationship of performance fluctuations between any two spatial points x_1 and x_2 :

$$C(x_1, x_2) = E[\{H(x_1, \omega) - \mu(x_1)\}\{H(x_2, \omega) - \mu(x_2)\}] \quad (6)$$

where x denotes the spatial coordinate vector within the physical domain of the Moso bamboo; ω represents an elementary event in the sample space;

$H(x, \omega)$ is the random field representing the specific mechanical property (such as tensile strength or elastic modulus) at location x ;

$E[\cdot]$, $\text{Var}[\cdot]$, and $\text{Cov}[\cdot]$ denote the mathematical expectation, variance, and covariance operators, respectively;

$\mu(x)$ and $\sigma^2(x)$ are the mean and variance functions at the spatial point x , respectively;

x_1 and x_2 represent any two arbitrary spatial coordinate points within the structural domain;

$C(x_1, x_2)$ is the autocovariance function quantifying the spatial correlation between points x_1 and x_2 .

3.2. Correspondence Between the Structural Characteristics of Moso Bamboo and Random Field Parameters

Moso bamboo, as a naturally evolved functionally graded biomass composite material, has its macroscopic heterogeneity fundamentally rooted in the non-uniform distribution of vascular bundles and parenchyma tissue at the mesoscopic level. The density and dimensions of vascular bundles in the cross-section exhibit regular variations along the radial direction, while the parenchyma primarily serves a filling and supporting role. The differentiated spatial arrangement of these two components constitutes the microscopic basis for the gradient variations in the material's macroscopic mechanical and physical properties. These mesoscopic structural characteristics endow the abstract parameters within the random field with explicit physical connotations.

- (1) Correspondence between axial fiber continuity and longitudinal correlation distance. The most prominent feature of Moso bamboo is its high specific axial tensile strength, which primarily relies on the vascular bundles. The vascular bundles, consisting of vessels surrounded by thick-walled fiber sheaths, grow continuously along the axial direction of the bamboo culm, spanning across internodes and serving as the load-bearing skeleton. In the random field, this continuity corresponds to the longitudinal correlation distance, θ_z . A large correlation distance indicates a high degree of coherence in the properties of adjacent elements along the axial direction. If the

strength at a specific point is low, the strength at several adjacent points above and below it will also be low, thereby forming a longitudinal weak band. Conversely, if θ_z is set too small, the strength and modulus will fluctuate abruptly along the axial direction, failing to simulate the long-range coherence of the Moso bamboo fibers.

- (2) Correspondence between circumferential random perturbation and circumferential correlation distance. Unlike the longitudinal direction, the fiber distribution in the culm wall of Moso bamboo exhibits stronger randomness in the circumferential direction. This is because, during the growth process, influenced by environmental factors such as soil pressure, wind load, and sunlight, the arrangement density of vascular bundles in the circumferential direction is uneven—being dense in some areas and sparse in others. This fluctuation in spatial arrangement maps to the circumferential correlation distance, θ_θ , in the random field. A smaller circumferential correlation distance indicates a limited circumferential coherence scale, meaning that the strength changes relatively quickly in the circumferential direction. This explains why, during actual tensile testing, crack initiation within the cross-section often has multiple starting points, and the transverse propagation of cracks is frequently hindered by adjacent high-strength fibers.
- (3) Correspondence between radial functional gradient and the mean trend term. The most distinct feature of the Moso bamboo cross-section is that it is dense on the outside and sparse on the inside. The bamboo cortex side features dense vascular bundles, resulting in high strength and modulus; conversely, the bamboo pith side contains abundant parenchyma tissue, resulting in low strength. This exponential gradient from the outside to the inside is a deterministic biological pattern, rather than a random phenomenon. In the random field, this deterministic pattern is extracted as the mean trend term, $\mu(\gamma)$. During modeling, the vascular bundle volume fraction extracted using the digital image processing technique detailed in Section 2 is utilized to fit a function that varies with the radius. Consequently, the random field does not fluctuate around a constant but randomly oscillates around this varying curve. This formulation ensures that the model can accurately capture the massive stiffness discrepancy between the bamboo cortex and pith, as well as the interlaminar shear stress induced by this gradient.
- (4) Correspondence between the coefficient of variation and cell wall growth defects. Even within a small, localized region at the same height and radial depth, the degree of lignification, secondary wall thickness, and cell lumen size of the fiber cell walls will exhibit statistical deviations due to the influence of growth seasons, water supply, and local illumination. These micro-scale uncertainties are uniformly mapped to the variance term or the coefficient of variation (CV) within the random field. The CV demarcates the maximum amplitude by which the random field deviates from the mean trend. A large CV indicates numerous internal defects within the material and severe strength fluctuations, whereas a small CV indicates a relatively homogeneous material.

3.3. Establishment of the 3D Random Field

Prior to constructing the three-dimensional (3D) random field model, a probabilistic characteristic analysis of the raw experimental data must first be conducted. Figure 10 illustrates the statistical distributions of tensile strength, elastic modulus, and vascular bundle volume fraction. As indicated by the histograms and fitted curves, each mechanical parameter exhibits a pronounced central tendency in a statistical sense and fundamentally conforms to the characteristics of a Gaussian distribution. This provides a solid mathematical foundation for the subsequent application of a Gaussian random field in numerical simulations.

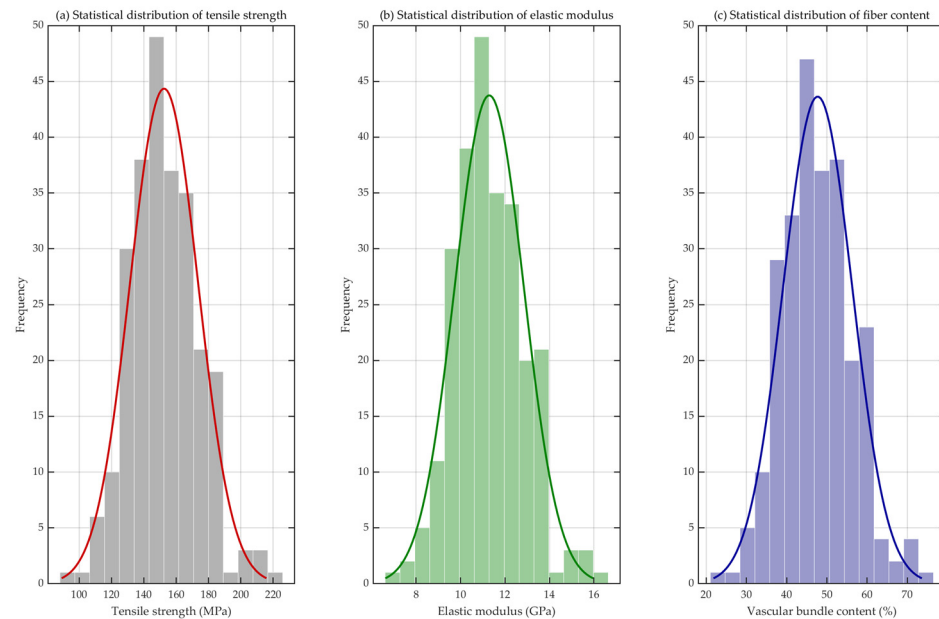


Figure 10. Statistical distributions of Moso bamboo properties: (a) Tensile strength; (b) Elastic modulus; (c) Vascular bundle content.

In an idealized academic model, Moso bamboo, as a naturally growing entity, theoretically exhibits statistical characteristics (e.g., mean, variance, and correlation functions) at every internal point that dynamically vary with the position coordinate X . Defining a three-dimensional (3D) non-stationary Gaussian random field $H(X, \omega)$, its autocovariance function no longer satisfies translation invariance, which is expressed as:

$$C_{xx}(x_1, x_2) = \sigma(x_1)\sigma(x_2)\rho(x_1, x_2) \quad (7)$$

where $\rho(x_1, x_2)$ is a complex non-stationary correlation kernel.

Within the physical space of Moso bamboo, this implies that the nodal coherence near the bamboo cortex side might be significantly higher than that on the bamboo pith side, and this coherence produces unpredictable fluctuations with increasing height z . Therefore, this study introduces the additive decoupling mapping theory. The physical essence of this theory is to attribute the dispersion of material properties to the superposition of genetic growth laws and random environmental perturbations.

The most prominent feature of Moso bamboo is its radial functional gradient. Through non-linear regression analysis of the experimental results, this study constructs the deterministic trend function:

$$T(r, z) = \left[\alpha \exp\left(\beta \frac{r - R_{in}}{R_{out} - R_{in}}\right) + \gamma \right] \cdot \psi(z) \quad (8)$$

where $T(r, z)$ denotes the deterministic trend operator, which represents the mathematical expectation (mean value) of the mechanical property (e.g., tensile strength or elastic modulus) at the spatial coordinates (r, z) under the assumption of a zero-mean random field.

r represents the radial coordinate, indicating the actual radial distance from the calculation point to the central axis of the bamboo culm; z represents the longitudinal coordinate, indicating the height of the current point from the ground.

R_{in} and R_{out} denote the inner radius (corresponding to the bamboo pith side) and the outer radius (corresponding to the bamboo cortex side) of the Moso bamboo culm, respectively.

$\frac{r-R_{in}}{R_{out}-R_{in}}$ is the normalized radial distance, a dimensionless parameter ranging from 0 (at the inner surface) to 1 (at the outer surface). The physical significance of introducing this term is to ensure that the exponential growth pattern of the vascular bundles depends heavily on the relative position within the culm wall, independent of the absolute wall thickness.

α , β and γ are the radial trend calibration parameters. These are constants determined through non-linear regression analysis (e.g., Least Squares Estimation) based on the 255 sets of measured samples. Specifically, γ is the baseline term (related to the initial property near the bamboo pith), α is the magnitude term controlling the overall amplitude of the radial gradient, and β is the rate term governing the steepness of the exponential growth along the radius.

$\psi(z)$ is the longitudinal correction function. It serves as a scaling factor to describe the variation in mechanical properties along the growth height z , effectively capturing the longitudinal macroscopic evolution pattern (i.e., properties decreasing from the top section to the bottom section).

Within the framework of random field decoupling theory, the deterministic trend term embodies the macroscopic property evolution characteristics of the Moso bamboo material governed by biological growth laws. Utilizing the vascular bundle volume fraction distribution data extracted via the digital image processing techniques in Chapter 3, in conjunction with the 255 sets of measured mechanical samples, a non-linear regression calibration was performed on the radial trend operator using the least squares method. An exponential growth model was adopted for the fitting process, and the specific fitted parameter results are presented in Table 3. The exponential growth model is expressed as follows:

$$T_r = a \cdot \exp(b \cdot r) + c \quad (9)$$

Table 3. Summary of regression parameters for the deterministic trend operator of radial properties.

Target Property	Amplitude Parameter a	Growth Rate b	Baseline Value c
Tensile strength	48.6	1.82	102.34
Elastic modulus	5.41	1.78	5.7

As shown in Table 3 above, the growth rate parameter b for both tensile strength and elastic modulus is highly consistent. This mathematically corroborates that the radial gradient evolution of both properties is fundamentally governed by the vascular bundles. Parameter c accurately reflects the baseline performance of the innermost bamboo pith region, thereby establishing the minimum threshold for the mechanical resistance distribution across the entire cross-section.

During the establishment of the three-dimensional (3D) digital twin model for Moso bamboo, the spatial coherence of mechanical properties and the cross-correlation between variables jointly constitute the core criteria for model reliability. This is achieved by deeply integrating the anisotropic correlation kernel function with the bivariate cross-correlation matrix. By imposing synergistic constraints on strength and stiffness within the 3D physical space, the model effectively reproduces the radial gradient pattern of Moso bamboo, characterized by a dense outer layer and a sparse inner core.

When constructing a multivariate joint random field, it is imperative to ensure that the parameter coupling relationships within the numerical model possess a genuine physical foundation. As a natural biomass composite material, the macroscopic mechanical properties of Moso bamboo are highly dependent on the distribution density of its internal vascular bundle fibers.

As illustrated by the 3D spatial relationship of the measured data in Figure 11, the tensile strength and elastic modulus of Moso bamboo do not evolve independently; rather, both exhibit a pronounced synchronous enhancement trend with the increase in local vascular bundle volume fraction. These three variables collectively form a rigorous physical coupling surface. This synchronous enhancement mechanism, dictated by the underlying mesoscopic structure, leads to a strong positive correlation between macroscopic strength and stiffness. Consequently, when establishing the random field in this section, a bivariate correlation coefficient matrix is introduced based on these empirically measured patterns.

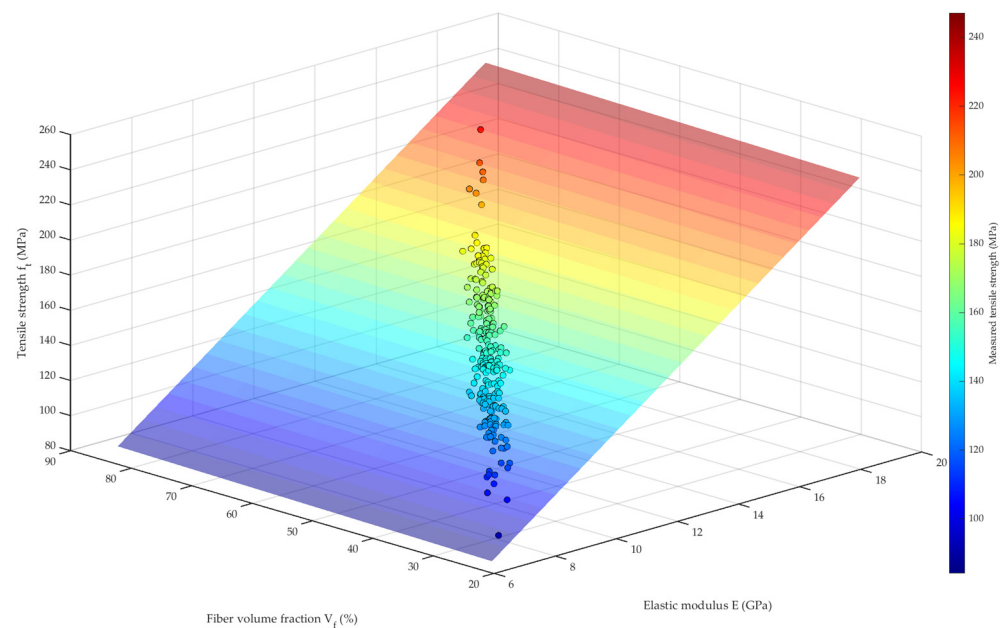


Figure 11. Three-dimensional spatial distribution of the tensile strength, elastic modulus, and vascular bundle volume fraction of Moso bamboo.

The fundamental fitting relationship among the three variables is expressed as follows:

$$f_t = 0.5 + 13.21E + 0.06V_f \quad (10)$$

where f_t denotes the tensile strength, E denotes the elastic modulus, and V_f denotes the vascular bundle volume fraction.

To realize the correlation between strength and modulus, a joint probability density function must be constructed. The cross-covariance matrix is defined as:

$$C_{biv} = \begin{bmatrix} C_{ff}(h) & C_{fE}(h) \\ C_{Ef}(h) & C_{EE}(h) \end{bmatrix} \quad (11)$$

where C_{biv} is the bivariate cross-covariance matrix.

h is the spatial lag vector, which can be understood as the spatial distance and direction between two points.

$C_{ff}(h)$ and $C_{EE}(h)$ represent the auto-covariance functions of tensile strength f and elastic modulus E , respectively.

$C_{fE}(h)$ and $C_{Ef}(h)$ represent the cross-covariance functions between tensile strength and elastic modulus.

The core operator lies in the cross-correlation term. According to the statistical results of the measured data, the two variables exhibit a strong positive correlation. By introducing

a coherence function, the spatial coherence and the variable correlation are integrated via a tensor product:

$$C_{fE}(x_1, x_2) = \rho_{fE} \sigma_f \sigma_E \rho_{sp}(\Delta X) \quad (12)$$

where x_1 and x_2 represent any two coordinate points in space.

ρ_{fE} : The Pearson correlation coefficient between the variables of strength and modulus.

σ_f, σ_E : The standard deviations of tensile strength and elastic modulus, respectively.

$\rho_{sp}(\Delta X)$: Spatial coherence function, characterizing the degree of spatial correlation between two points separated by a distance of ΔX .

By performing Pearson linear correlation analysis on the 255 sets of discrete data, the degree of linear coherence between the variables is quantified. The calculated correlation coefficient matrix is presented in Table 4.

$$\rho_{X,Y} = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (13)$$

Here, $\rho_{X,Y}$ generally refers to the Pearson linear correlation coefficient between variables X and Y .

Table 4. Pearson correlation coefficient matrix between mechanical parameters and physical indicators of Moso bamboo.

Parameters	Tensile Strength	Elastic Modulus	Vascular Bundle Volume Fraction
Tensile strength	1.0	0.8576	0.8674
Elastic modulus	0.8576	1.0	0.8832
Vascular bundle volume fraction	0.8674	0.8832	1.0

X_i and Y_i are the specific measured values of the i -th sample.

$\bar{X}$ and $\bar{Y}$ are the statistical average values of variables X and Y across all samples.

The statistical results in Table 4 reflect the intrinsic correlation between the vascular bundle distribution and the macroscopic mechanical properties of the Moso bamboo material. The cross-correlation coefficient between tensile strength and elastic modulus is 0.8576. From a mesoscopic perspective, vascular bundles, consisting of vessels surrounded by thick-walled fiber sheaths, serve as both the load-bearing skeleton for tensile strength and the primary source of axial stiffness.

Furthermore, the correlation coefficients of the vascular bundle volume fraction with tensile strength and elastic modulus are 0.8674 and 0.8832, respectively. This scientifically validates the methodology of utilizing the fiber distribution features extracted via DIP (Digital Image Processing) to drive the modeling of the deterministic trend term within the random field.

To capture the structural characteristics of Moso bamboo fibers, a three-dimensional (3D) separable exponential kernel was adopted:

$$\rho_{sp} = \exp \left(-\sqrt{\left(\frac{\Delta z}{\theta_z} \right)^2 + \left(\frac{\Delta r}{\theta_r} \right)^2 + \left(\frac{R_{avg} \Delta \theta}{\theta_s} \right)^2} \right) \quad (14)$$

where θ_z represents the longitudinal correlation length, aiming to simulate the long-range continuity of the fibers;

θ_r represents the radial correlation length, intended to capture the drastic variation along the thickness direction;

θ_s represents the circumferential correlation length, modeling the random distribution of the circumferential growth.

Figure 12 shows the 3D random field. By comparing the tensile strength field on the left with the elastic modulus field on the right, a high degree of spatial synchronization can be intuitively observed between the two fields. The deep red longitudinal stripes in the strength field appear as high-stiffness red regions at the corresponding coordinates in the modulus field; conversely, the blue low-strength regions are precisely aligned in both figures. In terms of physical essence, this reflects that the vascular bundles, as the reinforcing phase of Moso bamboo, simultaneously determine the material's tensile strength limit and its ability to resist deformation.

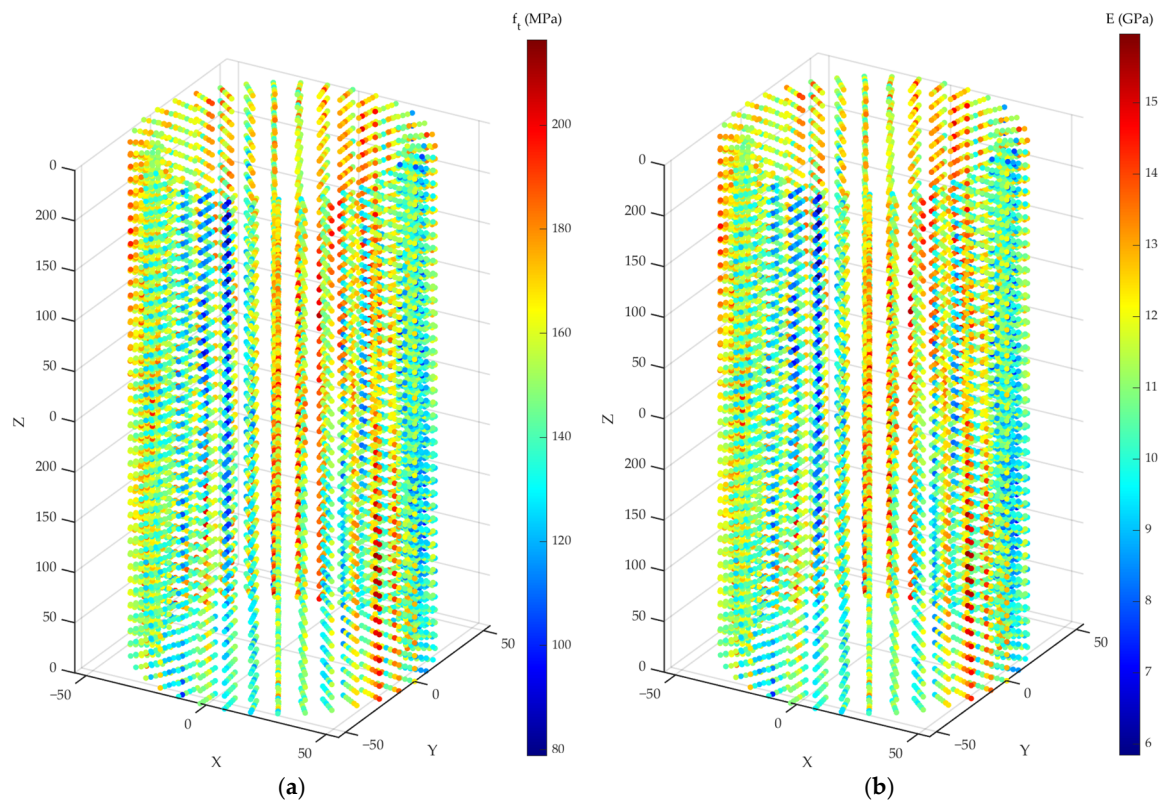


Figure 12. 3D random field (a) 3D tensile strength random field. (b) 3D elastic modulus random field.

Both solid cylinders exhibit a clear radial evolution pattern. The inner “bamboo pith” side presents a cool color palette, reflecting low strength and low rigidity, while the outer “bamboo cortex” side presents a warm color palette, indicating high strength and high rigidity. Driven by the deterministic trend operator, this distribution pattern successfully captures the biological characteristic of vascular bundles becoming exponentially denser from the inside out. This superposition of radial gradients and random fluctuations enables the model to realistically identify the locations within the component most prone to initial damage.

The stripe-like textures extending along the Z-axis in the figure confirm the effectiveness of the anisotropic correlation length parameters. This axial long-range coherence simulates the physical reality that Moso bamboo fibers are continuously arranged along the growth direction. Due to the high longitudinal synchronization of strength and modulus, stress flow tends to propagate along these high-stiffness stripes. If failure occurs in a specific stripe, the corresponding strength limit will lead to rapid stress redistribution, thereby enabling precise prediction of the typical splitting failure mode of Moso bamboo parallel to the grain.

Following the mathematical derivation of the additive decoupling for the three-dimensional (3D) random field, it is necessary to further elucidate the mechanical rationality of this method at the physical boundaries of the Moso bamboo. Moso bamboo constitutes a continuous spatial biological tissue from the bamboo pith to the bamboo cortex. When artificially separating and superimposing the deterministic trend term and the stationary random fluctuation term, the crucial step lies in verifying whether this process triggers non-physical numerical discontinuities or stress boundary layer effects at the extreme boundary values.

Under the framework of the additively decoupled 3D random field for the axial tensile strength of Moso bamboo, modeling strength and stiffness in isolation leads to the emergence of non-physical paradoxes. The final decision, however, achieves synergy between the two at the foundational mathematical level through the introduction of a cross-covariance tensor:

$$C_{biv}(x_1, x_2) = \begin{bmatrix} C_{ff}(x_1, x_2) & \rho_{fE}\sigma_f\sigma_E\rho_{sp}(\Delta X) \\ \rho_{Ef}\sigma_E\sigma_f\rho_{sp}(\Delta X) & C_{EE}(x_1, x_2) \end{bmatrix} \quad (15)$$

where $C_{biv}(x_1, x_2)$ denotes the bivariate cross-covariance matrix between two spatial coordinate points x_1 and x_2 ;

$C_{ff}(x_1, x_2)$ and $C_{EE}(x_1, x_2)$ represent the auto-covariance functions of the tensile strength f and elastic modulus E , respectively;

ρ_{fE} and its symmetric counterpart ρ_{Ef} is the Pearson correlation coefficient between the tensile strength and elastic modulus;

σ_f and σ_E denote the standard deviations of the tensile strength and elastic modulus, respectively;

$\rho_{sp}(\Delta X)$ represents the spatial coherence function, which captures the degree of spatial correlation at a distance interval of ΔX .

The random field established in this section guarantees that when the vascular bundle volume fraction in a specific region is relatively low, the strength and modulus of that region will decrease synchronously. Driven by the axial correlation, local low-strength zones are prone to interconnect longitudinally, forming continuous weak bands. Upon loading, these bands are highly susceptible to stress concentration, which allows for an accurate depiction of the typical splitting failure process of Moso bamboo parallel to the grain. Compared to the scattered speckle distribution generated by a pure non-stationary Gaussian random field, the anisotropic bivariate coupled 3D solid random field model demonstrates significantly stronger explanatory power regarding the underlying mechanical mechanisms.

As illustrated in Figure 13, the realizations generated by this model exhibit a high degree of physical fidelity. By comparing the tensile strength realization with the vascular bundle volume fraction realization, a clear spatial correspondence can be observed: the red strength peaks occurring at specific height and angle coordinates precisely match the red high-content peaks in the corresponding spatial contour maps. The dark blue valley regions in the contour maps represent the inherent weak zones of the material. The coupled model ensures that both strength and stiffness remain simultaneously low in these specific regions, thereby realistically triggering the weakest-link failure mechanism. Furthermore, the ridge-like structures extending along the z -axis in the figures corroborate the accurate capture of fiber continuity by the correlation parameters.

In physical essence, this reflects the fact that vascular bundles, serving as the primary reinforcing phase of Moso bamboo, simultaneously govern the material's ultimate tensile strength and its resistance to deformation.

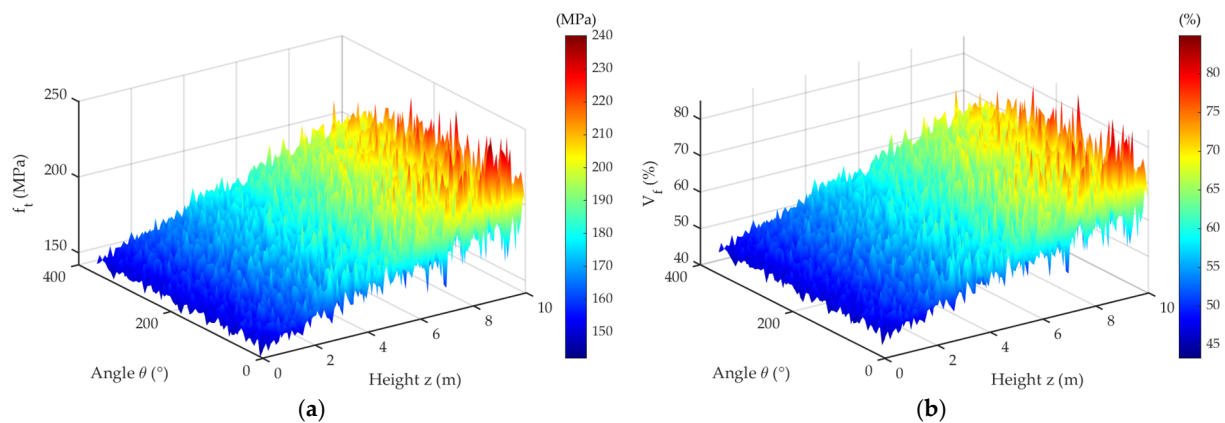


Figure 13. Random field cloud map. (a) Tensile strength random field. (b) Vascular bundle volume fraction random field.

3.4. Statistical Fidelity Verification of the Random Field

Although the spatial contour maps generated by the random field visually simulate the anisotropic texture of Moso bamboo, their validity as input sources for structural reliability analysis must be established on the foundation of rigorous statistical fidelity. In this section, 10^5 spatial node properties of the random field are generated utilizing the Monte Carlo method. The statistical characteristics of these generated nodes are then back-checked and validated against the 255 sets of measured sample data. This process aims to verify the reconstruction accuracy of the proposed model across three dimensions: statistical moments, probability distributions, and physical properties.

The core of this verification lies in ensuring that the statistical characteristics of the random field outputs—such as the first-order mean, second-order variability, and correlation coefficient—precisely converge to the experimental input values. The comparative results are presented in Table 5.

Table 5. Comparison Table of Statistical Characteristics between Samples Generated from Random Field and Measured Data.

Statistical Indicator	Experimental Input Value	Random Field Simulated Value	Relative Error (%)
Mean tensile strength (Mpa)	152.5	152.23	0.22
Mean elastic modulus (GPa)	11.3	11.38	0.71
Coefficient of variation for strength	0.1365	0.138	0.3
Strength–stiffness coupling coefficient	0.8576	0.9996	14.2

As indicated in Table 5, the relative errors for the marginal statistical moments—including the mean tensile strength, mean elastic modulus, and the coefficient of variation for strength—are strictly maintained below 1%, demonstrating exceptional numerical convergence. Conversely, the strength–stiffness coupling coefficient exhibits a higher relative error of 14.2%. This discrepancy is primarily rooted in the structural rigidity of the mathematical coupling framework within the three-dimensional anisotropic random field. While the first- and second-order marginal moments are pointwise or spatially aggregated properties that converge rapidly in Monte Carlo simulations, the coupling coefficient represents a second-order joint cross-correlation governed by the cross-covariance tensor.

In the numerical formulation, both the strength and stiffness fields are heavily driven by the identical mesoscopic vascular bundle trend operator and simultaneously constrained by the separable exponential correlation kernel. This inevitably introduces a mathematical overestimation of spatial synchronization, forcing the two variables to co-fluctuate almost perfectly along the longitudinal fiber paths. In reality, however, natural Moso

bamboo exhibits independent sub-grid anomalies; localized micro-structural defects, such as secondary cell wall voids, localized fiber debonding, or varying degrees of lignification, can significantly impair the ultimate tensile strength without causing a commensurate degradation in the elastic modulus. The stochastic model, by smoothing out these independent, micro-scale residual fluctuations through spatial discretization and averaging effects, artificially tightens the linear interdependence toward 0.9996. Nevertheless, this minor over-estimation represents a sound and legally conservative approximation for macro-structural reliability analysis, and the overall results conclusively validate the statistical convergence and mathematical reliability of the constructed bivariate cross-covariance operator when processing large-scale spatial node data.

3.5. Comparative Verification of Spatial Distribution Morphology and the Theoretical Model Morphological Fidelity of Probability Distributions

As depicted in the probability density distribution comparison of tensile strength in Figure 14, the red curve simulated by the random field exhibits a high degree of overlap with the gray histogram of the experimental observations. This excellent goodness-of-fit indicates that the model not only accurately captures the central tendency of the data but also comprehensively reflects the skewness and kurtosis characteristics of the measured samples. Consequently, this ensures that when calculating the structural failure probability, the model provides genuinely reliable predictions for the low-probability, high-risk left-tail region of the distribution.

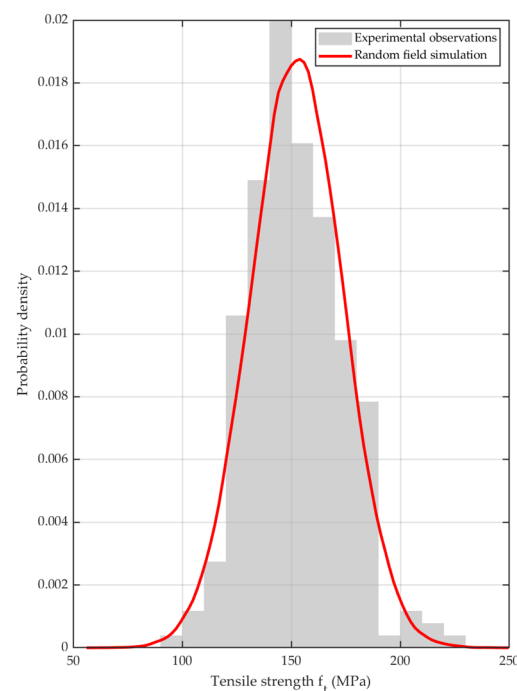


Figure 14. Probability density of tensile strength.

3.6. Interval Probability Analysis of Member Tensile Performance Based on the Random Field Model

In the preceding sections, a high-fidelity three-dimensional anisotropic bivariate coupled random field model was successfully constructed and validated using 255 sets of experimental data. The statistical fidelity verification results demonstrate that the relative errors for core indicators—including the mean, coefficient of variation, and strength–stiffness correlation coefficient—are all within 1%, and the probability density curves exhibit a high degree of overlap with the empirical histograms.

Therefore, it is urgent to develop an engineering evaluation method capable of objectively quantifying the dual impact of spatial variability and sampling uncertainty.

This section utilizes the established random field model as a material digital twin platform. By integrating non-parametric statistics and probability box (p-box) theory, we conduct an interval probability analysis of the ultimate tensile strength of Moso bamboo members, providing a quantitative basis for the safety assessment and material grading of bamboo structures.

Under the condition of spatial variability, the macroscopic ultimate tensile strength of a member is no longer a deterministic value, but an interval variable directly governed by the internal random defect field. Based on the Monte Carlo simulation results presented in Section 3.4, this study treats these properties as a strength sequence derived from a large population of member samples. To avoid mathematical errors introduced by prior distribution assumptions, the absolute extremes are extracted from this sample sequence. Consequently, the absolute fluctuation interval of the member's ultimate tensile capacity is defined without the necessity of any distributional assumptions:

$$R^I = [R^L, R^U] = [\min(R), \max(R)] \quad (16)$$

As indicated in Table 6, under the current calibrated spatial variability level of the material, the ultimate tensile strength of the bamboo member is strictly bounded within the interval of [98.85 MPa, 190.74 MPa]. The physical and mechanical implications of this interval are well-defined: the lower bound represents the minimum bearing capacity that the member can exert under the most unfavorable combination of micro-defects and spatial correlations, serving as the core control benchmark for triggering weakest-link structural failure. Simultaneously, the interval width acts as a macroscopic indicator that quantitatively measures the extent of the influence of material spatial variability on the macroscopic mechanical response of the member.

Table 6. Statistical results of the interval parameters for ultimate tensile strength.

Sample Size	Upper Bound (MPa)	Lower Bound (MPa)	Interval Width (MPa)	Sample Mean (MPa)
10^5	190.74	98.85	91.89	151.83

On this basis, the empirical cumulative distribution function (ECDF) is further employed to characterize the probabilistic properties of the structural resistance. As a representative non-parametric estimation method, the ECDF curve is driven by the sampled data, free from any specific distribution type assumptions. Its mathematical expression is defined as follows:

$$F_N(r) = \frac{1}{N} \sum_{i=1}^N I(R_i \leq r) \quad (17)$$

where I is the indicator function, which takes a value of 1 when the condition $R_i \leq r$ is satisfied, and 0 otherwise.

Although the ECDF faithfully reflects the distribution characteristics of the sampled data, finite sample sizes inevitably introduce epistemic uncertainty. To incorporate this uncertainty into structural safety assessment, this study constructs a probability box (p-box) for the member's ultimate tensile resistance based on the Kolmogorov–Smirnov (KS) non-parametric test theory, building upon the ECDF foundation.

Probability box (p-box) theory indicates that, at a given significance level ∂ , the unknown true cumulative distribution function, $F(r)$, is constrained within an interval probability band with a high confidence level of $1 - \partial$, satisfying: $F^L(r) \leq F(r) \leq F^U(r)$.

Considering the rigorous safety requirements in civil engineering, this study adopts a 95% confidence level for the envelope. The calculation formulas for the lower and upper envelope functions are as follows:

$$\begin{cases} F^L(r) = \min\left(0, F_N(r) - \frac{D_\partial}{\sqrt{N}}\right) \\ F^U(r) = \max\left(1, F_N(r) - \frac{D_\partial}{\sqrt{N}}\right) \end{cases} \quad (18)$$

where D_∂ is the critical constant for the Kolmogorov–Smirnov (KS) test. At a significance level of $\partial = 0.05$, the critical value is typically taken as $D_{0.05} = 1.358$.

As illustrated in Figure 15, the gray shaded region represents the probability box (p-box) rigorously constructed based on interval probability theory. This p-box comprehensively and conservatively bounds the dual risks stemming from the material's inherent spatial variability and sampling uncertainty. In contrast to traditional single-curve distribution fitting, the interval probability band establishes a defined safety margin in the critical left-tail region of the distribution. This safety boundary effectively mitigates the risk of underestimating the failure probability caused by inappropriate distribution assumptions, thereby providing a more robust and reliable reference for the safety assessment of Moso bamboo structures.

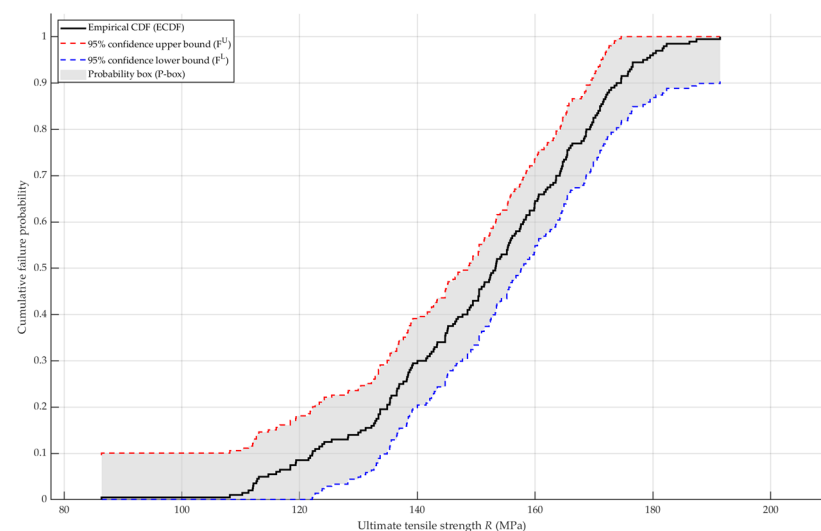


Figure 15. Interval Probability Distribution of Ultimate Tensile Strength of Bamboo Members.

After establishing the resistance interval and probabilistic boundaries of the Moso bamboo members under the empirical baseline condition, this section further investigates how fluctuations in the material's underlying variability drive the evolution of its macroscopic mechanical performance. Moso bamboo of varying culm ages and from diverse growth environments exhibits substantial discrepancies in the dispersion degree of its internal vascular bundle distribution and micro-defects. Consequently, this study adopts the coefficient of variation, a core input parameter of the 3D random field—as the control variable to conduct a sensitivity evolution analysis on the member's resistance interval.

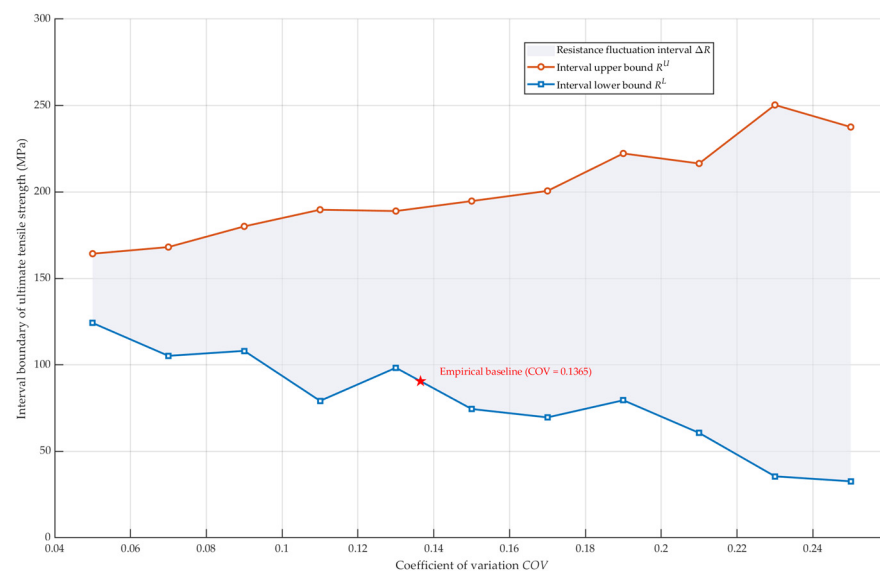
By systematically adjusting the COV of the strength variable while maintaining constant characteristic parameters, such as the spatial correlation lengths, the interval probability analysis is repeatedly executed. The lower bound, upper bound, and interval width at each variability level are meticulously extracted, and the corresponding calculation results are summarized in Table 7.

Table 7. Evolution Data of Resistance Intervals under Different Material Coefficients of Variation.

COV	Upper Bound (MPa)	Lower Bound (MPa)	Interval Width (MPa)	Interval Skewness Ratio
0.05	164.60	124.28	40.33	1.89
0.07	175.93	106.16	69.77	1.75
0.09	178.87	104.82	74.06	1.60
0.11	184.26	99.12	85.14	1.51
0.13	202.19	78.49	123.70	1.38
0.15	199.39	64.57	134.32	1.76
0.17	208.18	50.62	157.56	1.73
0.19	232.77	72.88	159.89	0.92
0.21	224.46	45.37	179.09	1.41
0.23	228.54	36.98	191.56	1.45
0.25	246.14	43.11	203.02	1.11

where the interval skewness ratio is defined as $(R_U - R_{\text{mean}})/(R_{\text{mean}} - R_L)$. A ratio greater than 1 implies that the degradation rate of the interval lower bound is significantly higher than the enhancement rate of the upper bound.

Figure 16 illustrates the sensitivity evolution curves of the resistance interval of raw bamboo components to the material coefficient of variation. The macroscopic ultimate resistance interval of Moso bamboo members is extremely sensitive to microscopic material variability. As the coefficient of variation (COV) increases from 0.05 to 0.25, the interval width experiences a non-linear surge from 40.33 MPa to 203.02 MPa, amplifying by more than a factor of five. More critically, this evolution exhibits a pronounced asymmetric nature: the interval skewness ratio generally remains greater than 1. This indicates that the degradation rate of the lower bound of the ultimate resistance (a decrease of 65.3%) is significantly higher than the enhancement rate of the upper bound (an increase of 49.5%), with the former being 1.32 times that of the latter.

**Figure 16.** Evolution Curve of Sensitivity of Resistance Intervals of Bamboo Members to Material Coefficient of Variation.

The anomalous interval skewness ratio of 0.92 observed at a coefficient of variation of 0.19 is fundamentally driven by the superposition of inherent statistical fluctuations in extreme value extraction during large-scale Monte Carlo simulations and the long-tail effect of the random field model. Specifically, in this simulation batch, the upper bound of tensile strength abnormally surged to 232.77 MPa, whereas the lower bound did not continue to drop but instead rebounded to 72.88 MPa. This implies that this

particular realization happened to randomly generate ultra-strong member specimens with an exceptionally ideal vascular bundle arrangement, while accidentally failing to capture the worst-case specimens containing extreme weak zones. Furthermore, governed by the weakest-link failure mechanism of Moso bamboo parallel to the grain, the lower bound of the member's ultimate capacity does not attenuate indefinitely but is constrained by the physical lower limit imposed by the inherent mechanical properties of the parenchyma cell matrix. Conversely, the mathematical nature of the random field model easily extends toward the right tail under high variability levels, theoretically allowing the upper limit of the strength to reach extreme values. Consequently, when this incidental increment in the upper bound strength exceeds the physically constrained decrement of the lower bound, the interval skewness ratio naturally experiences a transient drop below 1.0 within its general evolution trend of remaining greater than 1.

This asymmetric evolution thoroughly validates the weakest-link mechanism inherent in the tensile failure of Moso bamboo from a macroscopic resistance perspective. Specifically, the load-bearing capacity of the member is not dictated by its average strength, but is fundamentally governed by the most vulnerable local bands within the random field. An increase in the COV drastically heightens both the occurrence probability and the severity of these extreme weak zones, thereby precipitously deteriorating the lower limit of the member's resistance.

In summary, the application of interval probability theory for evaluating Moso bamboo members not only effectively circumvents the epistemic uncertainties introduced by artificially assumed probability distribution models, but also further elucidates the governing role of the weakest-link mechanism on structural tensile performance through sensitivity analysis. For practical engineering applications, it is highly recommended to rigorously inspect the material variability of Moso bamboo. Specifically, when the coefficient of variation (COV) of the material is substantial, proactive measures—such as strict material grading or structural reinforcement—should be implemented to effectively mitigate the risk of brittle failure in bamboo structures.

4. Conclusions

In this study, a comprehensive experimental investigation and a highly detailed 3D probabilistic modeling framework were conducted to characterize the spatial variability and bivariate coupling mechanisms of the tensile properties of Moso bamboo. The main conclusions are as follows:

- (1) The macroscopic mechanical properties of Moso bamboo exhibit significant spatial variability and multi-scale dependence. The tensile strength and elastic modulus parallel to the grain display a distinct longitudinal decreasing gradient pattern, with the top section (5–8 m) approximately 15% and 12% higher in average tensile strength and elastic modulus, respectively, than the bottom section (1–3 m). This longitudinal gradient, coupled with high data dispersion (coefficients of variation ranging from 8.5% to 23.0%), is fundamentally controlled by the vascular bundle distribution.
- (2) The 3D anisotropic bivariate coupled random field model effectively reconstructs the natural structural logic of Moso bamboo. The radial deterministic trend function captures the exponential increase in vascular bundle density from the pith to the cortex, while the anisotropic correlation kernel accurately reflects the disparity between longitudinal long-range coherence and circumferential random fluctuations.
- (3) A 3D anisotropic bivariate coupled random field model was established. By effectively capturing the continuous spatial correlation and reflecting the measured true natural cross-correlation coefficient of 0.8576 between tensile strength and elastic mod-

ulus, the model overcomes the limitations of traditional deterministic homogeneous assignments.

- (4) The model demonstrates exceptional statistical fidelity and engineering reliability. Relative errors between the random field realizations and the measured data for core indicators—including the mean, coefficient of variation, and correlation coefficient—are consistently controlled within 1%. Furthermore, the constructed interval probability box (P-box) rigorously bounds the macroscopic ultimate tensile resistance of full-scale bamboo members within [98.85, 190.74] MPa. Sensitivity analysis reveals an asymmetric degradation mechanism (with an Interval Skewness Ratio stabilized at approximately 1.38), quantitatively substantiating that full-scale bamboo members follow a brittle “weakest-link” failure mechanism governed by localized continuous low-strength weak bands. This framework establishes a robust theoretical foundation for refined, reliability-based safety design of modern bamboo structures.

Beyond theoretical reliability assessment, the proposed interval probability framework and 3D random field model offer profound practical implications for the construction and timber industries. For engineered bamboo products such as glued-laminated bamboo (glulam), the model enables variability-informed material grading, allowing manufacturers to optimize strategic layup designs by positioning lamellae with higher lower-bound strengths in extreme stress zones, thereby maximizing structural reliability and minimizing waste. Furthermore, the sensitivity evolution model provides data-driven guidance for forestry and processing workflows. Harvesting protocols can be optimized to select Moso bamboo with minimal heterogeneity (lower COV), while the digital twin framework can identify probable continuous weak bands during industrial processing. This insight informs precision-cutting strategies and targeted structural reinforcements, ultimately maximizing the yield and safety of high-quality bamboo construction materials.

While the proposed 3D random field model provides a robust statistical representation of spatial variability, it is essential to interpret its predictive capabilities with caution. As a stochastic framework, it generates statistically equivalent realizations rather than deterministic physical replicas (exact digital twins) of specific bamboo culms. Consequently, predicting the exact physical locations of structural weak zones in a specific individual specimen remains beyond the scope of purely probabilistic simulations. For practical engineering applications, evaluating the statistical probability of localized weak bands is feasible, but future research integrating this probabilistic framework with Non-Destructive Testing (NDT) technologies is recommended to achieve high-precision, individualized weak-zone identification.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Raw Tensile Data of Bamboo.

Sample Number	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fiber Ratio (%)
1S001	148.80	12.45	45.30
1S002	166.91	12.26	54.11
1S003	161.39	11.88	49.94
1S004	161.56	12.01	51.56
1S005	208.29	15.42	69.35
1S006	140.35	10.33	41.01
1S007	186.97	13.87	62.57
1S008	170.36	12.54	54.63
1Z001	154.47	11.49	48.61
1Z002	129.37	11.81	35.40
1Z003	181.02	13.38	59.72
1Z004	167.01	12.36	56.19
1Z005	182.49	13.52	59.45
1Z006	149.50	11.04	45.91
1Z007	169.83	12.58	54.16
1Z008	183.59	13.49	60.44
1Z009	159.17	11.84	50.84
1X001	148.80	11.02	45.30
1X002	103.25	13.44	26.70
1X003	181.45	10.78	59.95
1X004	148.51	11.00	48.79
1X005	150.79	11.11	46.40
1X006	146.85	10.94	46.25
1X007	183.30	13.59	58.85
1X008	156.44	11.57	50.54
1X009	147.43	10.92	46.05
2S001	156.15	11.53	49.09
2S002	151.18	11.20	47.94
2S003	178.90	9.21	58.52
2S004	165.11	12.24	53.78
2S005	136.58	10.13	42.45
2S006	185.32	13.81	61.19
2S007	105.47	7.87	27.24
2S008	124.18	9.24	37.17
2S009	161.86	12.01	50.54
2Z001	109.33	8.17	30.96
2Z002	178.90	12.65	58.52
2Z003	174.49	12.97	59.01
2Z004	143.00	10.91	44.30
2Z005	128.10	9.57	37.97
2Z006	131.69	9.69	38.60
2Z007	147.90	10.99	45.20
2Z008	143.71	10.68	42.88
2X001	117.94	8.75	31.28
2X002	137.23	10.21	45.33
2X003	156.14	11.50	49.90
2X004	123.81	8.33	37.30
2X005	127.97	9.45	38.95
2X006	146.96	10.86	46.59
2X007	128.77	9.54	37.56
2X008	163.59	12.14	51.37
3S001	113.47	8.40	32.88
3S002	170.48	12.62	55.30
3S003	128.81	9.54	38.50
3S004	171.59	12.72	56.80
3S005	135.04	10.01	38.93

Table A1. *Cont.*

Sample Number	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fiber Ratio (%)
3S006	127.23	9.40	37.61
3S007	169.50	14.02	63.64
3S008	123.77	9.16	35.80
3S009	158.33	11.67	49.37
3S010	175.18	12.93	57.98
3Z001	147.58	10.87	44.12
3Z002	171.11	12.77	53.70
3Z003	170.48	12.47	53.50
3Z004	172.19	12.75	55.20
3Z005	159.51	11.81	50.69
3Z006	137.03	10.17	42.84
3Z007	137.95	9.72	42.10
3Z008	167.08	12.44	53.49
3Z009	147.18	10.91	46.22
3X001	158.65	11.76	48.91
3X002	134.83	10.00	39.40
3X003	127.03	9.41	39.50
3X004	124.35	9.20	37.40
3X005	134.96	10.01	40.40
3X006	155.01	11.48	46.50
3X007	119.61	11.95	33.10
3X008	137.51	10.22	41.40
4S001	169.11	12.54	54.83
4S002	172.29	11.40	54.58
4S003	171.83	12.72	54.44
4S004	185.83	13.78	60.91
4S005	129.86	9.65	36.78
4S006	128.10	9.58	38.37
4S007	136.23	10.13	42.71
4S008	179.89	11.27	48.29
4Z001	130.99	9.66	39.02
4Z002	136.13	10.09	41.47
4Z003	157.72	11.70	51.37
4Z004	132.71	9.93	40.21
4Z005	146.33	10.81	42.80
4Z006	135.84	10.05	42.83
4Z007	166.59	12.30	54.20
4Z008	135.69	10.09	39.13
4Z009	137.27	10.05	41.80
4X001	141.47	10.37	45.37
4X002	143.00	10.55	44.31
4X003	154.95	11.51	47.63
4X004	153.11	11.23	47.82
4X005	122.00	10.20	34.50
4X006	149.13	11.07	46.88
4X007	171.89	12.68	58.13
4X008	99.14	12.40	53.22
4X009	146.42	10.86	47.13
4X010	163.29	12.08	51.49
5S001	155.11	13.14	51.67
5S002	158.89	11.80	49.73
5S003	147.82	10.90	45.53
5S004	183.24	13.55	60.22
5S005	145.31	10.77	45.44
5S006	154.56	11.41	47.84
5S007	130.00	9.68	36.24
5S008	148.32	10.95	45.66
5S009	143.48	10.60	42.13
5Z001	186.37	13.79	60.55
5Z002	127.03	11.07	39.50

Table A1. *Cont.*

Sample Number	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fiber Ratio (%)
5Z003	133.47	9.84	39.99
5Z004	169.09	12.52	53.47
5Z005	151.08	11.21	45.61
5Z006	148.06	11.04	42.86
5Z007	129.91	9.62	38.78
5Z008	154.18	11.42	46.55
5X001	148.57	11.01	47.47
5X002	116.35	9.95	28.10
5X003	152.05	11.30	47.92
5X004	142.69	10.55	42.94
5X005	147.54	10.93	44.98
5X006	131.11	9.72	39.22
5X007	169.29	12.51	55.70
5X008	162.69	12.03	51.69
6S001	141.72	10.56	42.43
6S002	140.04	10.34	43.80
6S003	122.08	9.09	33.92
6S004	170.48	15.05	53.51
6S005	204.58	11.10	69.76
6S006	156.23	11.54	49.99
6S007	162.29	12.01	50.44
6S008	174.98	12.95	57.04
6S009	179.70	13.28	58.52
6Z001	152.91	11.28	49.15
6Z002	148.54	10.99	46.48
6Z003	153.48	11.33	47.16
6Z004	169.39	12.52	55.81
6Z005	133.23	11.76	47.40
6Z006	116.26	8.61	30.92
6Z007	158.88	11.82	51.10
6Z008	149.18	11.06	44.64
6X001	174.82	12.98	58.37
6X002	140.57	10.37	41.45
6X003	149.31	11.13	46.94
6X004	180.25	13.37	60.05
6X005	127.12	12.42	35.60
6X006	166.86	12.35	54.86
6X007	93.08	6.93	23.94
7S001	181.42	13.44	60.04
7S002	106.90	7.79	30.14
7S003	203.38	15.05	68.62
7S004	160.35	11.84	53.33
7S005	129.32	9.60	39.57
7S006	169.30	10.06	63.30
7S007	211.08	15.59	70.30
7S008	135.01	10.00	40.33
7Z001	148.22	11.00	47.03
7Z002	154.01	11.37	45.10
7Z003	131.05	9.74	38.52
7Z004	159.36	11.81	51.48
7Z005	155.18	11.48	52.08
7Z006	137.95	10.22	42.10
7Z007	176.52	10.31	43.20
7Z008	159.01	11.82	50.51
7X001	166.50	12.28	52.52
7X002	130.49	9.66	39.13
7X003	142.85	10.52	43.79
7X004	123.23	9.12	33.55
7X005	162.94	12.14	53.26

Table A1. *Cont.*

Sample Number	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fiber Ratio (%)
7X006	111.08	8.27	32.61
7X007	127.39	12.83	41.30
7X008	165.06	12.13	53.39
7X009	134.54	10.06	42.56
8S001	165.76	12.27	52.70
8S002	184.46	13.68	60.20
8S003	158.02	11.65	49.47
8S004	213.64	15.81	71.88
8S005	146.69	10.78	45.95
8S006	136.93	10.06	44.23
8S007	172.19	13.25	55.20
8S008	172.27	12.76	54.60
8S009	182.99	13.55	63.30
8Z001	128.94	9.56	39.51
8Z002	148.57	10.92	45.72
8Z003	135.00	9.94	37.97
8Z004	148.89	10.98	43.29
8Z005	134.96	8.32	40.40
8Z006	124.99	9.29	34.67
8Z007	130.90	9.64	39.12
8Z008	165.99	12.28	52.26
8Z009	162.84	12.09	53.32
8X001	181.07	13.38	58.55
8X002	162.33	12.01	48.67
8X003	143.60	10.57	45.87
8X004	106.80	10.89	28.30
8X005	151.84	11.28	48.20
8X006	149.82	11.10	47.66
8X007	177.87	13.17	58.40
8X008	148.50	10.91	45.53
8X009	158.14	11.70	48.92
9S001	127.10	9.44	37.43
9S002	179.81	11.28	60.20
9S003	160.34	11.89	48.73
9S004	180.86	13.41	59.43
9S005	169.83	12.55	54.78
9S006	224.60	16.62	75.83
9S007	133.34	9.89	41.38
9S008	175.01	12.07	51.48
9Z001	162.31	12.03	53.96
9Z002	180.08	13.30	57.17
9Z003	122.37	9.03	34.08
9Z004	135.54	10.48	40.30
9Z005	126.08	9.30	37.50
9Z006	167.11	12.30	52.44
9Z007	148.87	11.07	44.89
9Z008	183.35	13.57	60.14
9X001	179.81	13.32	60.20
9X002	142.21	10.54	43.33
9X003	138.04	10.21	43.46
9X004	105.68	8.89	27.70
9X005	129.30	9.60	37.80
9X006	146.92	10.84	45.90
9X007	179.76	13.32	58.87
9X008	156.80	11.60	49.62
10S001	146.53	10.84	45.33
10S002	158.76	11.75	49.97
10S003	135.34	10.00	42.00
10S004	146.34	10.85	44.53
10S005	129.13	9.61	39.42

Table A1. Cont.

Sample Number	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fiber Ratio (%)
10S006	199.84	14.83	66.62
10S007	174.60	12.92	56.80
10S008	159.94	11.88	50.65
10Z001	147.17	10.89	45.89
10Z002	125.56	9.31	36.83
10Z003	173.40	12.82	53.87
10Z004	125.59	9.31	35.51
10Z005	173.31	12.87	55.32
10Z006	155.01	13.65	46.50
10Z007	184.78	10.92	62.40
10Z008	139.00	10.34	41.74
10Z009	135.52	10.02	40.02
10X001	150.39	11.10	45.22
10X002	117.16	8.70	32.42
10X003	138.09	10.25	40.71
10X004	158.37	11.71	51.24
10X005	152.31	11.21	47.56
10X006	172.99	12.82	54.19
10X007	137.27	10.17	41.80
10X008	135.54	10.04	40.30

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